

STATE-OF-THE-ART REPORT ON ANCHORAGE TO CONCRETE

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For the first time concrete anchoring knowledge based on worldwide test programs is presented in a state-of-the-art document. Performance of different anchor types, including cast-in-place, grouted, expansion, torque-controlled, chemical (adhesive), and undercut anchors is presented in both uncracked and cracked concrete. Failure modes in tension and shear, spacing and edge distance, group performance, and load displacements are offered. The effect of loading conditions for structural supports, column bases, and pipe supports as well as base plate flexibility, how load is transferred to anchors, and ductility are discussed. Design criteria and existing code requirements, both domestic and foreign, are presented.

KEYWORDS: Adhesive anchors; anchorages; anchors; anchor groups; base plates; bolts; cast-in-place anchors; chemical anchors; code requirements; combined loads; compression zone; concrete; cracked concrete; creep; deformation; design criteria; drilling; ductility; dynamic loads; edge distance; embedment; expansion anchors; failure modes; fatigue loads; fasteners; flexible base plates; grouting; loads; load transfer; load-displacement; post-installed anchors; preload; pullout; seismic loads; shear loads; slip; spacing; spalling; static loads; stiffness; studs; structural design; tensile strength; tension loads; tension zone; temperature; torque; torque-controlled anchors; ultimate strength; undercut anchor; yield strength.

FORWARD

This state-of-the-art report on anchorage to concrete is the first of a two-volume project being undertaken by ACI Committee 355. The second volume, currently being developed, is a design manual. This first volume includes no design aids or procedures, per se, but with emphasis on behavior will serve as the guide for preparation of the second volume.

Committee 355 is working with Committees 349 and 318 toward the objective of including the subject of anchorage to concrete in ACI 318-95.

ACI Committee Reports, Guides, Standard Practices, and Commentaries are intended for guidance in designing, planning, executing, or inspecting construction, and in preparing specifications. Reference to these documents shall not be made in the Project Documents. If items found in these documents are desired to be a part of the Project Documents, they should be phrased in mandatory language and incorporated into the Project Documents.

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TABLE OF CONTENTS

Chapter 1-Introduction, p 355.1R-2

- 1.1 Purpose
- 1.2 Significance of the subject
- 1.3 Scope

Chapter 2-Types of anchoring devices, p 355.1R-2

- 2.1 Introduction
- 2.2 Scope
- 2.3 Anchor systems
- 2.4 Cast-in-place systems
- 2.5 Post-installed systems

Chapter 3-Behavior of anchors, p 355.1R-9

- 3.1 Introduction
- 3.2 Behavior of anchors in uncracked concrete
- 3.3 Behavior of anchors in cracked concrete
- 3.4 Behavior of cast-in-place anchor bolts in uncracked concrete piers
- 3.5 References

Chapter 4-Design considerations, p 355.1R-53

- 4.1 Introduction
- 4.2 Functional requirements
- 4.3 Materials
- 4.4 Design basis
- 4.5 Construction practices
- 4.6 References

Chapter 5-Construction considerations, p 355.1R-60

- 5.1 Introduction
- 5.2 Shop drawings/submittals
- 5.3 Tolerances
- 5.4 Installation of anchors
- 5.5 Inspection
- 5.6 Grouting
- 5.7 Field problems

Chapter 6-Requirements in existing codes and specifications, p 355.1R-66

- 6.1 Introduction
- 6.2 Existing codes and specifications
- 6.3 Application and development of codes
- 6.4 References

Appendix A-Conversion factors, p 355.1R-71

Appendix B-Notations, p 355.1R-71

CHAPTER 1 -INTRODUCTION

1.1-Purpose

The purpose of this document is to summarize the current state of the art in anchorage to concrete.

1.2-Significance of the subject

To date, anchorage to concrete has received little attention in structural codes. Emphasis has been primarily on the tensile and shear capacities of anchorage devices. As designs became more sophisticated and analyses more exacting, more emphasis was placed on the transfer of loads through single anchors and anchor systems. It was recognized that performance of anchors controlled these load transfers, and that generally, failure modes at ultimate anchor capacities were important. There were no definitive design codes or anchorage performance criteria on which designers and installers could rely. Subsequently, a myriad of approaches were developed.

1.3-Scope

This state-of-the-art report summarizes anchor types and provides an overview of anchor performance and failure modes under various loading conditions in both uncracked and cracked concrete. It covers design and construction considerations and summarizes existing requirements in codes and specifications. References are given for further review.

CHAPTER 2 -TYPES OF ANCHORING DEVICES

2.1-Introduction

There are many types of devices used for anchoring structures or structural members to concrete. The design of anchorages, involving the selection and positioning of these devices has been based on the Engineer's experience and judgment, private test data, manufacturers' data, and existing (sometimes obsolete) code requirements. It is proposed to promote a design of anchorages that more consistently reflects the performance potential of each type of anchor.

2.2-Scope

This report relates to the most widely used types of anchor, in sizes ranging from 1/4 in. (6.35 mm) to 2 1/2 in. (63.5 mm) in diameter. Included for consideration are only those devices which can generally be considered bolt and insert-type



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anchors. Excluded from consideration are shear lugs, structural shapes, powder actuated fasteners, light plastic or lead inserts, hammer driven concrete nails, screw driven systems, and cables. These are excluded because there is a paucity of test data regarding their performance. The anchors included in this report are either commercially available or may be fabricated.

2.3-Anchor Systems

According to present practice, there are two broad groups of anchoring systems: cast-in-place systems (anchors installed before the concrete is cast) and post-installed systems (anchors installed in holes drilled after the concrete has been cast and cured). Table 2.1 identifies these two groups of anchors.

Table 2.1 -Types of anchors in concrete

<u>Cast-in-place systems</u>	
Embedded, nonadjustable	
Common bolts	Fig. 2.1
Hooked "J" & "L" bolts	Fig. 2.2
Threaded rod	Fig. 2.3
Reinforcing steel	Fig. 2.4
Threaded inserts	Fig. 2.5
Stud-welded plates	Fig. 2.6
Bolted connections	Fig. 2.7
Adjustable anchors	Fig. 2.8
<u>Post-installed systems</u>	
Bonded anchors	
Grouted anchors	
Headed bolts or anchor	Fig. 2.9
Chemical anchors	
With threaded rod	Fig. 2.10
With reinforcing steel	Fig. 2.11
Expansion anchors	
Torque-controlled	
Heavy-duty sleeve anchor	Fig. 2.12
Sleeve anchor	Fig. 2.13
Shell expansion anchor	Fig. 2.14
Wedge anchor	Fig. 2.15
Rock/concrete expansion anchor	Fig. 2.16
Deformation controlled	
Drop-in anchor	Fig. 2.17
Self-drilling anchor	Fig. 2.18
Stud anchor	Fig. 2.19
Undercut	
With predrilled under-cut hole	Fig. 2.20
Self undercutting	Fig. 2.20

2.4-Cast-in-place systems

2.4.1 - Embedded Anchors, Non - Adjustable - These anchors may have an end attachment, such as a coil loop, head, nut, or plate, which will enhance anchorage properties and develop full potential strength by means of bond, and/or bearing, or both. Typical examples of these anchors are:

Common bolts	- structural steel bolts placed with the head into the concrete. (Fig. 2.1)
Hooked "J" or "L" bolts	- bent, smooth or deformed threaded bars. Have been known to straighten out in pull-out tests. (Fig. 2.2)
Threaded rod	- straight threaded rod, usually with coarse threads. (Fig. 2.3)
Reinforcing steel	- Stock or trade-name reinforcing bar (Fig. 2.4)
Threaded inserts	- wire form or internally threaded ferrule inserts, or coils, usually manufactured with internal or external threads, with wire loop struts. Headed anchors made from smooth or reinforcing steel bar also fall into this category. (Fig. 2.5)
Stud welded plates	- steel plates which have smooth bent hooked bars, deformed bars, or headed stud anchors. (Fig. 2.6)

2.4.2 Bolted connections-These anchors consist of headed bolts, as embedded or through-connectors. (Fig. 2.7).

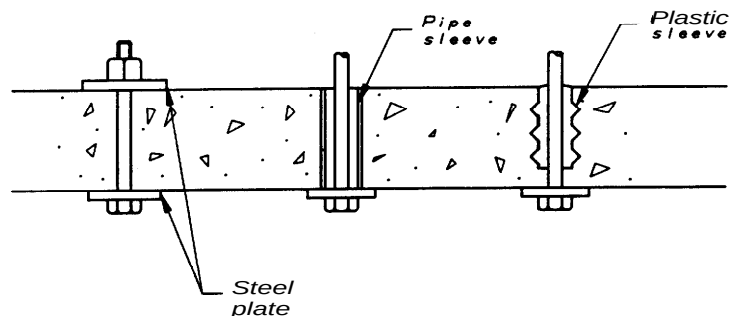


Fig. 2.7-Bolted connections

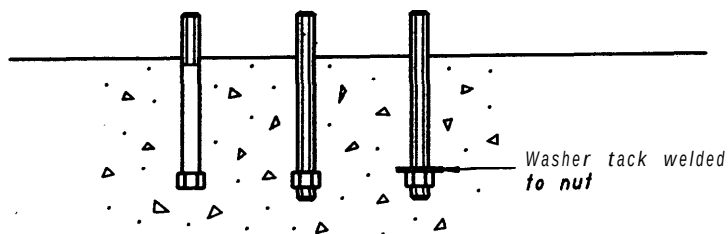
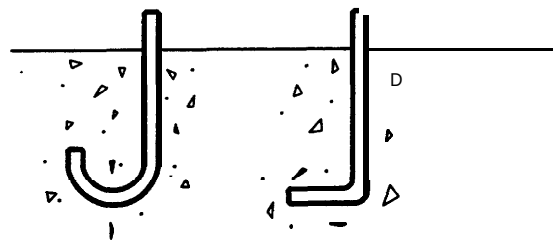


Fig. 2.1- Common bolts



Note : Either 'J' or 'L' bolts can be made from plain or threaded rod

Fig. 2.2-J- and L-bolts (not recommended)

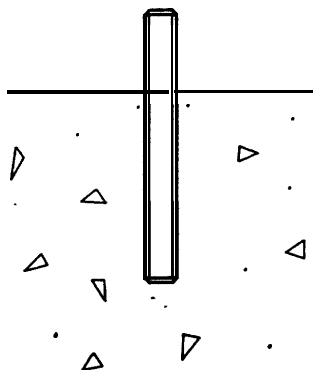


Fig. 2.3 – Threaded rod

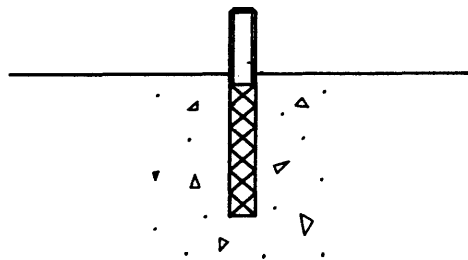


Fig. 2.4 -Reinforcing steel

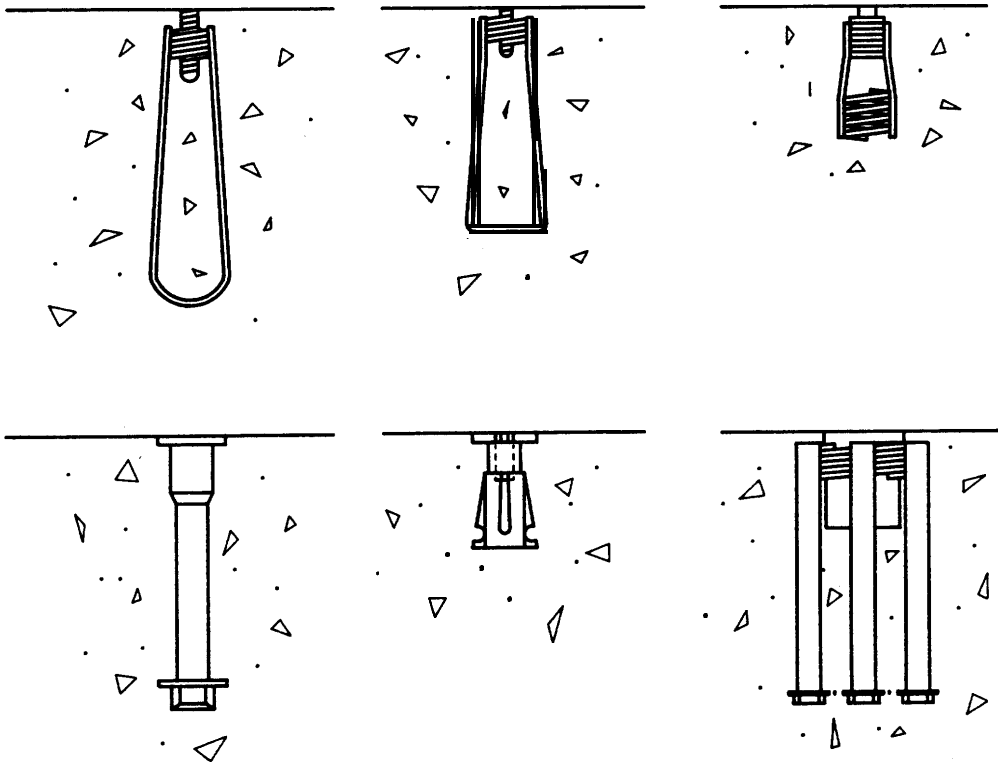


Fig. 2.5 – Threaded inserts

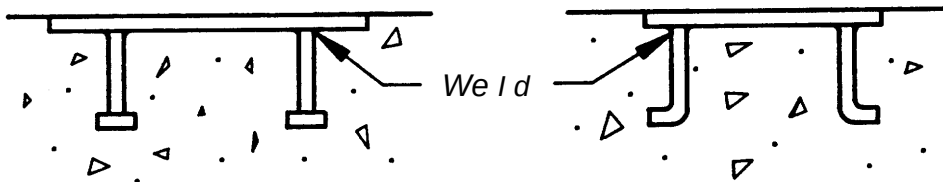


Fig. 2.6 – Stud- welded plates

2.4.3 Adjustable anchors—Adjustable anchors can be adjusted for lateral position or depth (Fig. 2.8). They are normally used for attaching large machines or equipment bases. On thin floor slabs, the anchor bolt often goes through the concrete to develop the required anchor capacity. When the floor slab or foundation is very thick, the anchor can develop full capacity and still be embedded in the concrete. After the equipment or machine base is installed and leveled, grout is used to fill the void around the anchor. The anchor then acts similar to a cast-in-place anchor.

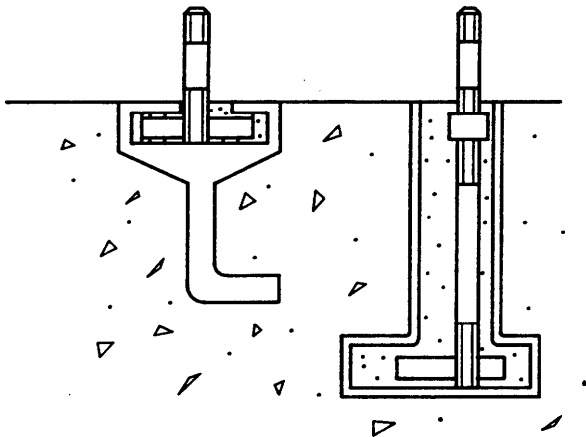


Fig. 2.8-Adjustable anchors

2.5-Post-installed systems

These anchors are installed in a hole drilled in the cured concrete. There are two basic groups of post-installed systems: bonded and expansion.

2.5.1-Bonded anchors

2.5.1.1 Grouted anchors—Grouted anchors are headed or headless bolts or threaded rods. They are set in predrilled holes with portland cement and sand grout or other commercially available premixed grout. (Fig. 2.9)

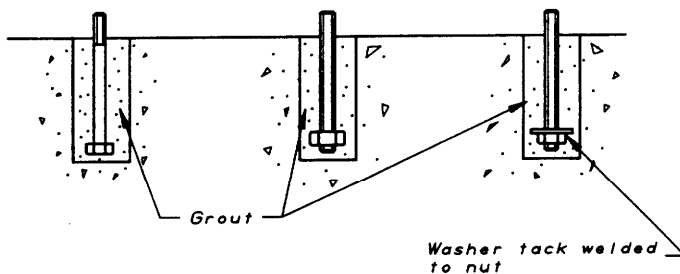


Fig. 2.9—Grouted anchors

2.5.1.2 Chemical anchors—Chemical anchors are usually threaded rods (Fig. 2.10) or deformed bars (Fig. 2.11) which are bonded in place with two-part chemical compounds of polyesters, vinyl esters, or epoxies. The chemicals are available in four forms: glass capsules, plastic cartridges, tubes, or bulk.

Glass capsules are inserted into the drilled hole, and then broken by the anchor rod when it is rotated and hammered into place, thereby mixing two components to cause a chemical reaction.

The plastic cartridges are used with a dispenser and a mixing nozzle which mixes the two parts, initiating a chemical reaction while installing the compound into the drilled hole. The anchor rod is then inserted into the hole completing the installation. The setting time is dependent on temperature, varying from a few minutes at 90° F up to several hours at 30° F.

The tube or “sausage” type contains two components which are mixed by kneading the tube, placing the mixture into the hole, and finally, inserting the anchor rod into the hole.

The bulk systems predominantly use epoxies, which are either premixed in a pot and used immediately, or pumped through a mixer and injected into the hole. The anchor is installed immediately afterward. Epoxies can be formulated to set up quickly or slowly (up to 36 hr curing time).

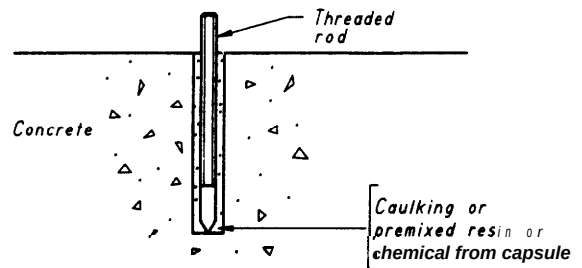


Fig. 2.10-Chemical anchor with threaded rod

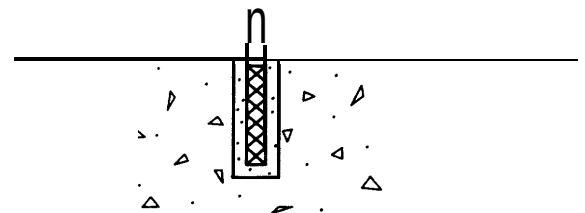


Fig. 2.11—Chemical anchor with deformed bar

2.5.2 Expansion anchors—Expansion anchors are designed to be inserted into predrilled holes and then expanded by either tightening the nut (torque controlled expansion anchor, Sections 2.5.2.1 to 2.5.2.5), hammering the anchor (deformation controlled expansion anchor, Sections 2.5.2.6 to 2.5.2.8), or expanding into an undercut in the concrete (undercut anchors, Section 2.5.2.9). These anchors transfer the tension load from the bolt to the concrete by expansion pressures or forces through friction and/or keying against the side of the drilled hole. They often are supplied with a bolt, nut, and washer. The following sections describe the various types of expansion anchors.

2.5.2.1 Heavy duty, torque controlled sleeve anchor—This type of anchor consists of a bolt or threaded rod with nut and washer on one end and a cone on the embedded end, (Fig. 2.12). Around the cone is a heavy expansion sleeve. Above the sleeve is a collapsible mechanism, sometimes made of plastic. A spacer sleeve extends to the surface of the drilled hole. The anchor is set by tightening the bolt head or nut which draws the cone up through the expansion sleeve, expanding it against the side of the drilled hole. The anchor develops its tensile capacity by means of a combination of keying into the concrete and high friction between the sleeve and concrete. The spacer sleeve aids in increasing the shear capacity. Tensile capacity depends on the strength of the bolt and its depth of embedment.

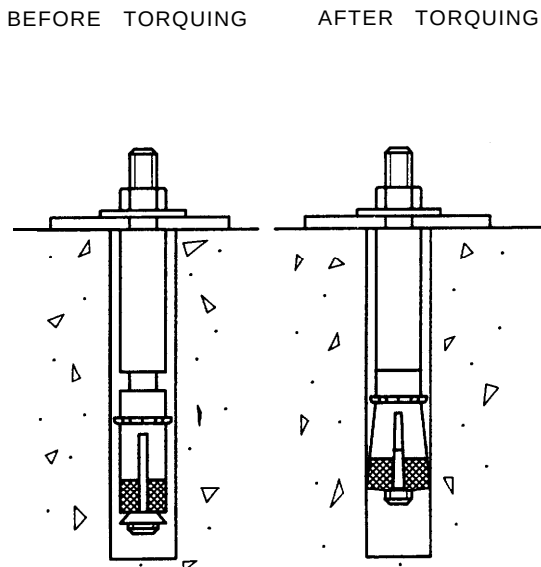


Fig. 2.12 – Heavy-duty, torque-controlled sleeve anchor

2.5.2.2 Sleeve anchors— The sleeve anchor consists of a steel stud, an expansion sleeve usually made of sheet metal, and a nut and washer (Fig. 2.13). The bottom of the steel stud has a uniformly tapered mandrel which has the same diameter at the end as the expansion sleeve. The entire length of the bolt below the washer is enclosed in a section or sections of the steel tubing. The bottom of the expansion sleeve is slit longitudinally to provide for expansion. When the nut is tightened, the tapered mandrel moves into and expands the sleeve which in turn bears against the wall of the hole. This anchor is used for medium and light holding requirements.

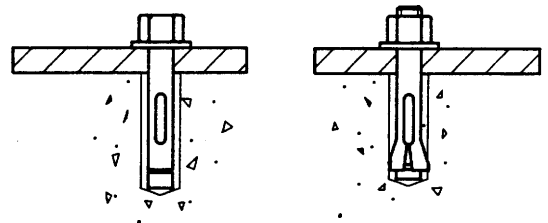


Fig. 2.13 – Sleeve anchor

2.5.2.3 Shell expansion anchors - The shell expansion anchor, (Fig. 2.14) is available in two types. One type consists of a two-piece shell held together by steel tabs with a tapered, internally threaded end plug. The second type consists of a two-piece shell section with two tapered steel cones, one at the top end and one at the bottom, which are held together by a steel spring at the center. The bottom cone is internally threaded to accept a bolt or stud. By torquing the fastener into the anchor, the steel cones expand the shell to bear against the wall of the hole.

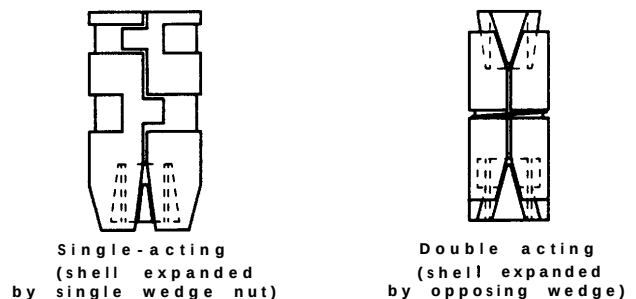


Fig. 2.14 – Shell expansion anchor

2.5.2.4 Wedge anchors—The wedge anchor, (Fig. 2.15) consists of a steel stud with a wedge at the bottom.

and washer. The bottom of the steel stud has a uniform tapered mandrel around which is positioned an expandable steel clip or separate steel wedges with protrusions. When the nut is tightened, the clip or steel wedges ride up on the tapered mandrel, wedging between the mandrel and the wall of the hole.

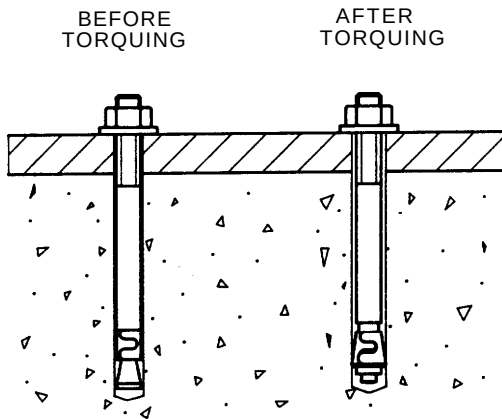


Fig. 2.15- Wedge anchor

2.5.2.5 Rock/concrete expansion anchor-The rock/concrete expansion anchor, (Fig. 2.16) consists of a stud bolt that is threaded on the top end for a hex nut. The bottom end consists of a large mechanical expansion anchor. To set the expansion anchor, the stud bolt is rotated in a clockwise direction. Grouting is optional down the center of the bolt to fill the annular space between the rod and the drilled hole for corrosion protection.

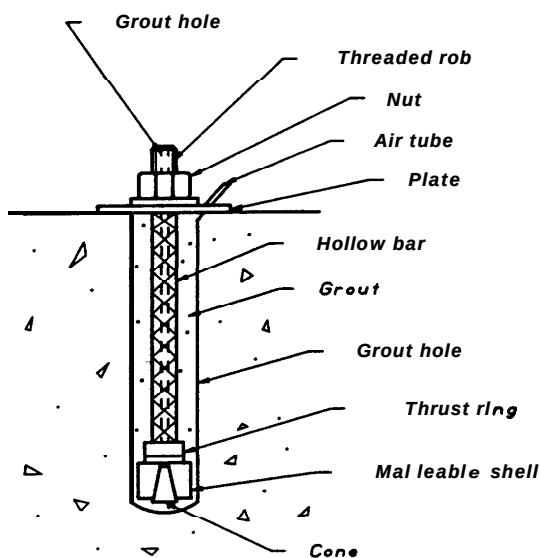


Fig. 2.16 – Rock/concrete expansion anchor (grouted)

2.5.2.6 Drop-in anchors-The drop-in anchor consists of a steel shell and an internal steel expander plug (Fig. 2.17). The anchor is internally threaded at the top end while the internal end is machined to a uniform taper, matching the shape of the steel plug inside the anchor. The lower portion of the shell is slit longitudinally into equal segments to allow the anchor to expand when the internal plug is hammered with a setting tool. By hammering the plug into the shell, the lower portion of the shell expands to bear against the wall of the hole.

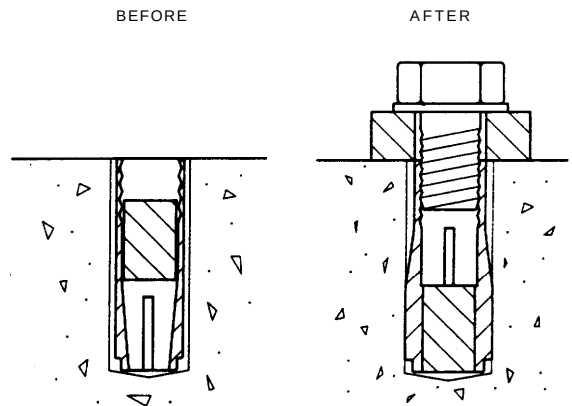


Fig. 2.17-Drop-in anchor

2.5.2.7 Self-drilling anchors-The self-drilling anchor, (Fig. 2.18) consists of a steel shell and a tapered steel end plug. The bottom of the shell has teeth for cutting its own hole in the concrete. The top of the shell is internally threaded to accept a bolt or stud. The bottom of the shell is expanded by hammer drilling the anchor over the steel plug. The plug expands the bottom of the shell which bears against the wall of the drilled hole.

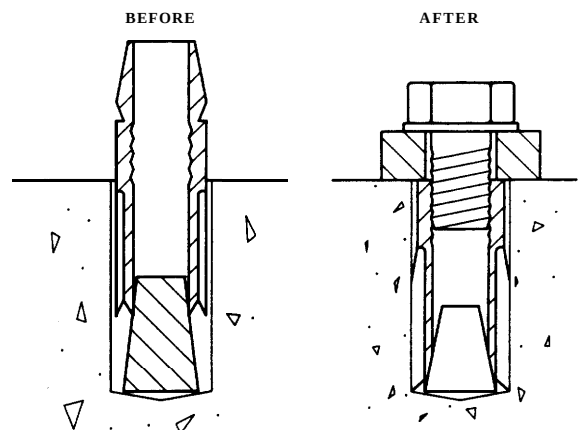


Fig. 2.18 -Self-drilling anchor

2.5.2.8 Stud anchors -The stud anchor consists of a steel stud, threaded at the top end, and has a drilled hole with longitudinal slits at the bottom end, which accepts a tapered steel plug (Fig. 2.19). The top of the threaded section is raised to provide a surface for hammering. By hammering the top of the stud, the tapered plug expands the bottom end of the bolt causing it to bear against the wall of the hole.

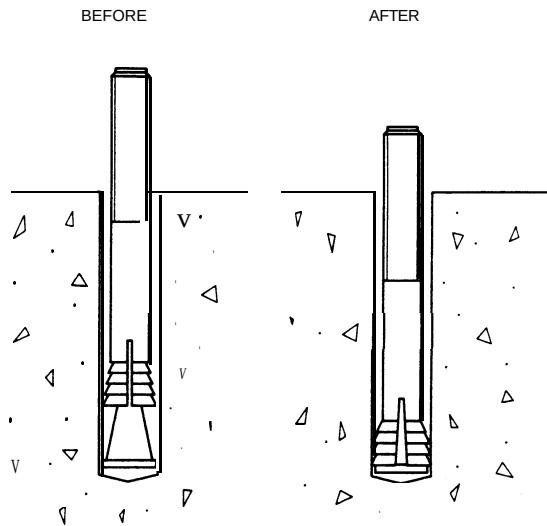


Fig. 2.19 – Stud anchor

2.5.2.9 Undercut anchors -There are two primary designs of undercut anchors available (Fig. 2.20). They all operate by keying and bearing against an undercut in the concrete at the bottom of the drilled hole. They cause little or no expansion force in the concrete, but generate high tensile-loading capacities.

The first type requires a second drilling operation to create an undercut at the bottom of the first drilled hole. The anchor is installed with the bottom of the expansion sleeve at the undercut. When the nut is tightened, the tapered expander plug expands the bottom of the steel expansion sleeve into the undercut.

The second type cuts its own undercut at the bottom of the drilled hole. A sleeve is hammered by a rotary hammer drill with a special setting tool. The bottom of the expansion sleeve is driven over a cone at the bottom of the hole. The bottom of the expansion sleeve has a sharp edge which, on expansion, cuts its own undercut into the wall of the hole. By tightening the nut, the

bolt and tapered cone are drawn up into the expansion sleeve, keeping the bottom of the expansion sleeve in the undercut.

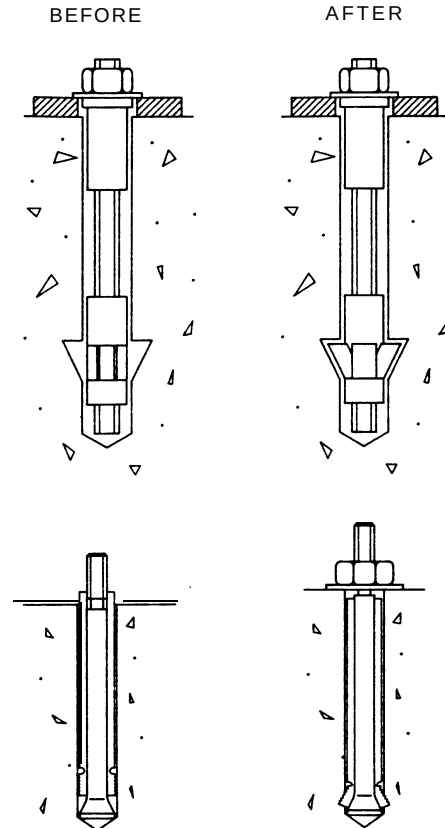


Fig. 2.20 – Undercut anchor

CHAPTER 3-BEHAVIOR OF ANCHORS

3.1 - Introduction

Understanding anchor behavior is necessary in specifying the appropriate anchorage for a given application. This includes an understanding of failure modes and strengths as well as load-displacement and relaxation characteristics of various anchor types. This chapter covers anchor behavior in uncracked concrete and in cracked concrete.

Anchors are primarily loaded through attachments to the embedded anchor. The loading can be in tension and shear or combinations of tension and shear (Fig. 3.1). They may also be subjected to bending depending on the details of shear transfer through the attachment. The behavior of anchors in tension is of primary importance and will be discussed first.

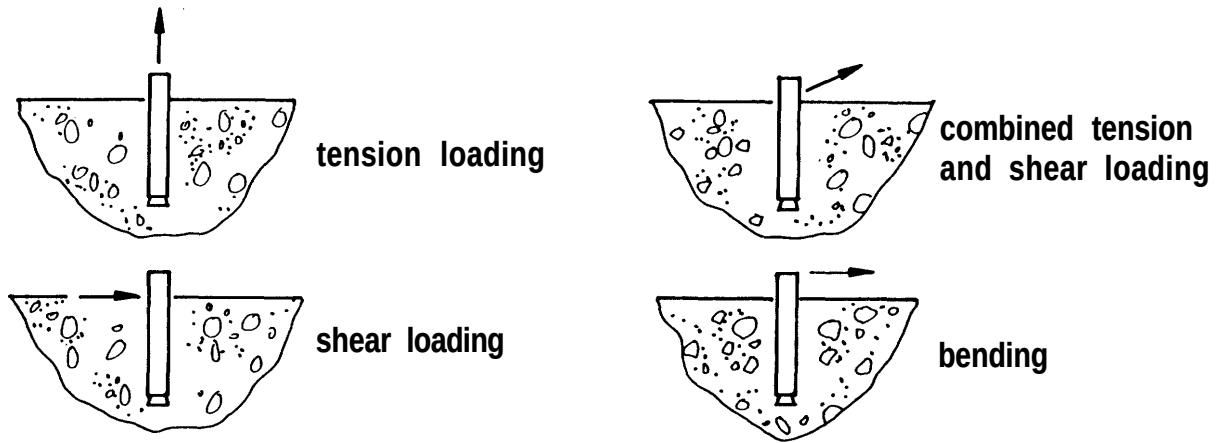


Fig. 3.1 -Possible loadings of anchors

By far, most anchor testing to date has been performed in uncracked concrete. While cracking occurs in almost all concrete, testing in uncracked concrete provides the basis for understanding anchor behavior.

3.2-Behavior of anchors in uncracked concrete

3.2.1 Load-displacement behavior and failure modes under tension loading- The five primary failure modes of anchors in tension are (Fig. 3.2):

- (a) Steel failure
- (b) Pull-out failure
- (c) Concrete splitting failure
- (d) Concrete cone failure
- (e) Spacing and edge cone failure

The various types of anchors have different displacement characteristics depending on preload, load transfer mechanism, and failure mode. Fig. 3.3(a)-3.3(c) present three load-displacement graphs. Fig. 3.3(a) gives the characteristic curves for headed and undercut anchors while Fig. 3.3(b) presents curves for torque-controlled, drop-in, and self-drilling expansion anchors. Fig. 3.3(c) gives load displacement curves for adhesive anchors. The displacements shown represent the displacement (slip) of the embedded anchor and the deformation of the concrete as well as the deformation of the anchor.

When a preload is applied to an anchor, typically by tightening the nut to a prescribed moment torque, the displacement caused by an externally applied load is affected. The preloaded

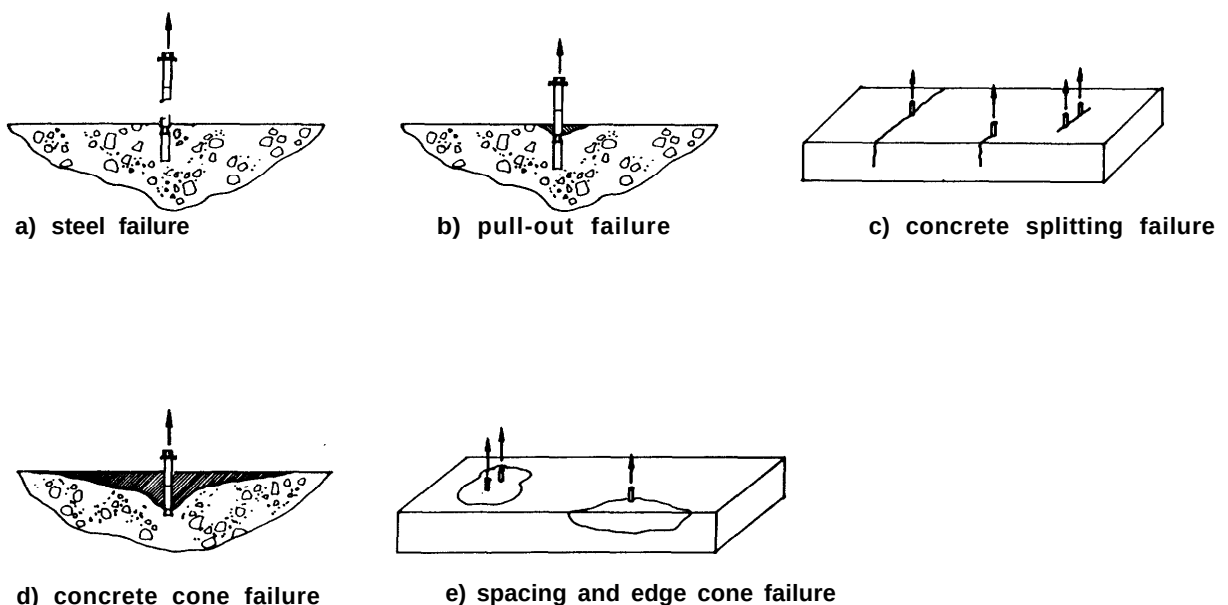
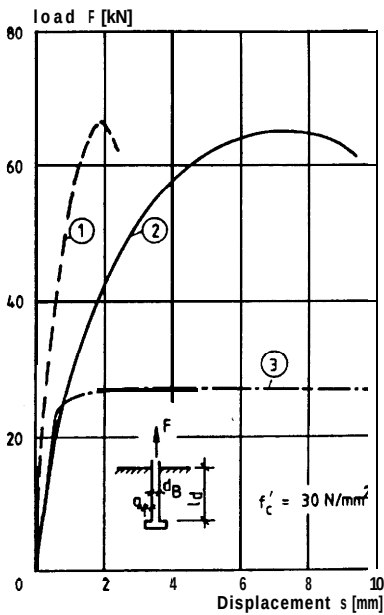
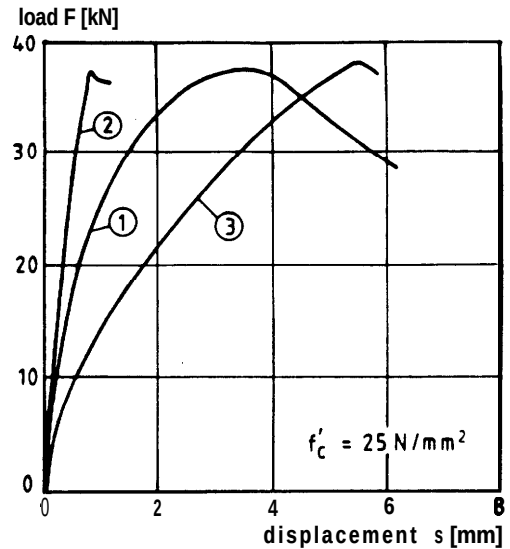


Fig. 3.2 – Typical failure modes of anchors loaded in tension



line	anchor type	d [mm]	dh [mm]	a [mm]	ld [mm]	failure
①	headed	19	32	6,5	80	concrete
②	undercut	12	18	3,0	80	concrete
③	headed	9.5	19	4,8	68	steel

Fig. 3.3(a) – Typical load-displacement relationships of headed and undercut anchors (from Rehm, Eligehausen, and Mallee 1988)



line	anchor type	bolt diameter mm	anchorage depth mm
①	torque controlled	10	65
②	drop-in	16	65
③	self-drilling	16	63

Fig. 3.3(b) – Typical load-displacement relationships of expansion anchors under tension loading (from Eligehausen and Pusill-Wachsmuth 1982)

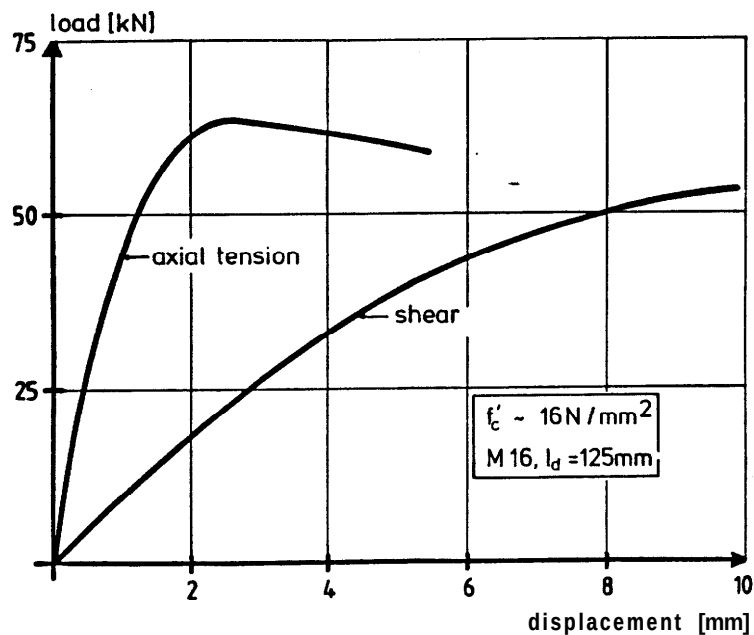


Fig. 3.3(c)- Typical load-displacement behavior of chemical anchors under tension and shear loading (from Eligehausen and Pusill- Wachsmuth 1982)

anchor shows little displacement with increasing external loading until the preload in the anchor (and resulting clamping force on the concrete) is overcome. The preload has no effect on the ultimate static tensile capacity of the anchorage, but significantly reduces the anchor total displacement.

In the case of steel failure (Fig. 3.3(a), Line 3) the ductility depends on the relationship between tensile strength and yield strength of the steel and the anchor length. Inelastic displacements of headed anchors due to concrete deformations under the head may be expected at relatively low loads unless preloaded. Increasing the bearing area under the head may reduce inelastic displacements but will have little influence on the failure load [compare Lines 1 and 2 in Fig. 3.3(a)]. Headed anchors that fail due to fracture of the concrete will exhibit a brittle failure (Fig. 3.3(b), line 2).

The behavior of drop-in anchors is dependent on the magnitude of the expansion force created in setting the anchor. When expanded properly during installation, high expansion forces are induced and the load displacement curve may remain almost linear up to failure [Fig. 3.3(b), Line 2].

The expansion force, at installation, of torque-controlled expansion anchors is smaller than that of drop-in anchors and, therefore, the displacements are larger for equal loads. If the external load exceeds the preloading force in the bolt generated by the torquing during installation, the spreading cone is pulled further into the sleeve, leading to increased displacement. At failure the deformations are much larger than for comparable drop-in anchors [Fig. 3.3(b)].

Self-drilling anchors show larger displacements in the total load range than torque-controlled expansion and drop-in anchors [Fig. 3.3(b)]. This happens because load transfer is mainly by mechanical interlock which causes high pressure on the concrete and large concrete deformations.

The displacement behavior of undercut anchors depends primarily on the bearing area (undercut area) and the installation torque. Therefore relatively large deformations may be expected with some undercut anchors while others exhibit elastic behavior well above service load [Fig. 3.3(a)].

Adhesive anchors exhibit elastic behavior up to nearly maximum load [Fig. 3.3(c)]. While the load-displacement curves of adhesive anchors exhibit relatively low coefficients of variation in

comparison to torque-controlled expansion and drop-in anchors, the bond strengths vary considerably depending on the adhesive component mix used and the installation procedure.

Under working loads all categories of anchors should behave elastically with little additional displacement after installation. However, at ultimate load a plastic behavior and in the case of cyclic loading only a limited strength degradation is desired. Fig. 3.3(a)-3.3(c) show that the actual load-displacement behavior of the currently available expansion, undercut, adhesive, and headed anchors differs somewhat from this plastic behavior.

Under sustained loads displacements will increase with time due to creep of concrete in the highly stressed load transfer area (bearing area in the case of headed or undercut anchors, contact area in the case of expansion anchors, bonded area in the case of adhesive or grouted anchors).

As an example, in Fig. 3.4 (see Seghezzi and Vollmer, 1982) the displacements of a torque-controlled expansion anchor loaded with a constant tensile force corresponding to approximately 70 percent of the static ultimate strength, are plotted as a function of load duration on a double logarithmic scale. It can be seen that the displacement velocity (tangent to the displacement-time curve) decreases with increasing time and, therefore, the displacements approach a limiting final value. The increase in displacements is smaller for lower sustained loads. If the load is increased after a sustained load test, the displacement curve is rather steep until it reaches the static envelope which is followed thereafter. Failure load and displacement at maximum load are not negatively influenced by a previous sustained load smaller than about 70 to 80 percent of the static failure load.

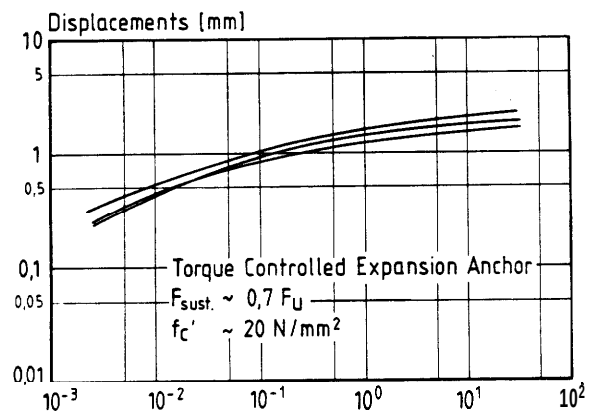


Fig. 3.4 -Increase of displacement during sustained loading

In principle, the same behavior is valid for cyclic loadings with up to 1×10^6 load repetitions and an upper load (where the cyclic load ranges between an upper and lower value, both of which are tension) smaller than about 50 percent of the static failure load (provided no fatigue failure of the bolt occurs). For higher upper loads the displacements may increase significantly and a fatigue failure of the concrete might occur (Rehm, Elgehausen, and Mallee 1988).

Sustained and cyclic loadings in the working-load range have the same influence on displacements and ultimate loads of headed anchors as for expansion and undercut anchors.

3.2.2 Relaxation -If headed anchors are preloaded, the initial force induced in the anchor is reduced with time due to creep of the highly stressed concrete under the anchor head. The final value of the tension force in the anchor depends primarily on the value of bearing stresses under the head, the concrete deformation and the anchorage depth. In typical cases the value of that final force will approach 40 to 80 percent of the initial preload (40 percent for short anchors, 80 percent for long anchors).

Torque-controlled expansion anchors are usually preloaded by tightening the nut during installation. This preload is essential for the proper performance of such anchors. In a typical installation, locally high concrete stresses are created around the embedded anchor wedges or expansion devices as the anchor is preloaded. Creep of concrete under these high stresses results in a slight movement of the embedded anchor, and in turn, in a reduction in the load in the bolt.

Fig. 3.5 shows a typical load-relaxation test (Burdette, Perry, and Funk 1987). Preload is plotted as a function of time. The shape of the curve is essentially the same for all anchors (including headed anchors). There is an exponential drop-off of load immediately after the applied tension is released, followed by a continued gradual diminishing of the load over an indefinite period. It is estimated that the final preload will be about 40 to 60 percent of the initial value. This is confirmed by other test data (Seghezzi and Vollmer 1982, and Wagner-Grey 1976). After retorquing the anchors, the process of load relaxation starts again, however, the final value of the preload is increased (Fig. 3.6). Retorquing even a short time after anchor installation can be effective (Wagner-Grey 1976).

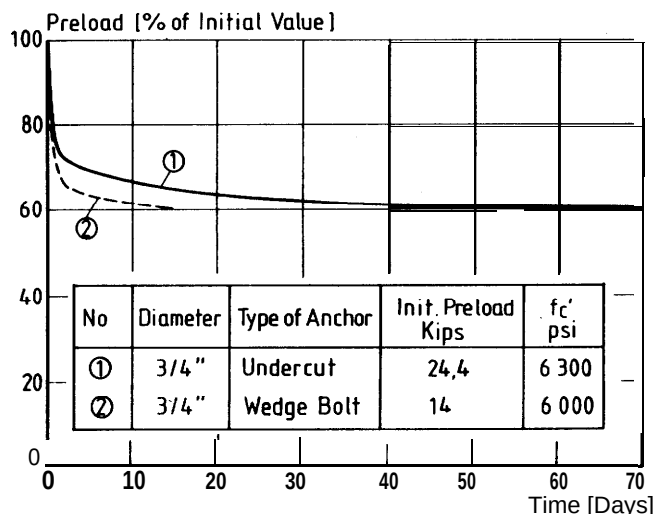


Fig. 3.5 -Reduction of preload as a function of time (after Burdette, Perry, and Funk 1987)

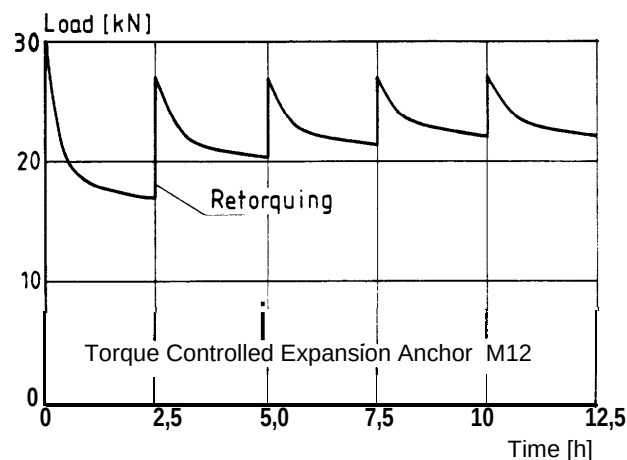


Fig. 3.6 -Influence of retorquing on the final value of preload (from Seghezzi and Vollmer 1982)

Chemical anchors are usually preloaded by applying a predefined torque. Because of the high stresses in the adhesive bond, the preload force in the anchor declines faster and the final value is less than for torque-controlled expansion and headed anchors.

Long-term relaxation and creep has been investigated in several studies. Four M16 diameter polyester anchors tested at loads of 25, 30, 38, and 40 kN (6, 7, 8.5, and 9 kips), showed displacements still increasing after 5 years, but ranging from 0.090 to 0.140 mm (0.0036 to 0.056 in.) (Elfgren, Anneling, Eriksson, and Granlund 1988). Creep tests were also performed on 20 M16 anchors for 3 years at various loads and

environmental conditions. At allowable working loads of 15 kN (3.4 kips), anchors tested indoors showed small creep, 0.10 to 0.40 mm (0.004 to 0.016 in.). However, anchors tested outdoors exhibited continually increasing creep. Those tested indoors at 30- and 45- kN (7 and 10 kips), loads exhibited continually increasing creep. A 4 month test on epoxy anchors showed creep less than 0.009 in. (0.2 mm) (Wiewel 1989).

The U.S. Army Corps of Engineers performed creep tests on polyester and epoxy anchors, subjecting the anchors to 60 percent of the anchor steel yield strength for 6 months. Cement and epoxy grouted specimens exhibited low slippage, 0.0013 to 0.0008 in. (0.03 to 0.02 mm), while polyester anchors exhibited approximately 30 times as much movement, 0.008 to 0.024 in. (0.2 to 0.6 mm) (Best, Floyd, and McDonald 1989).

3.2.3 Ultimate strength in tension

3.2.3.1 Steel failure-The strength of anchor steel controls failure when the embedment of the anchor is sufficient to preclude concrete failure and when the spreading forces are sufficiently high (expansion anchors) or the bearing area is sufficiently large (headed and undercut anchors) to preclude an anchor slip failure. The failure mode [Fig. 3.2(a)] is rupture of the anchor steel with ductility dependent on the type of anchor steel and embedment length. The ultimate strength can be determined from Eq. 3.1.

$$F_u = A_s \times f_{ut}, \text{ lb} \quad (3.1)$$

where

A_s = tensile stress area, in.²

f_{ut} = ultimate tensile strength of steel, psi

For given material properties and anchor dimensions this case defines the upper limit for the tensile-load-carrying capacity.

Fig. 3.7 shows a comparison of the failure loads of headed anchors measured in tests to the values predicted by Eq. 3.1. Because the theoretical failure load was calculated with the nominal steel strength, the ratios of actual to predicted tensile capacity are larger than one.

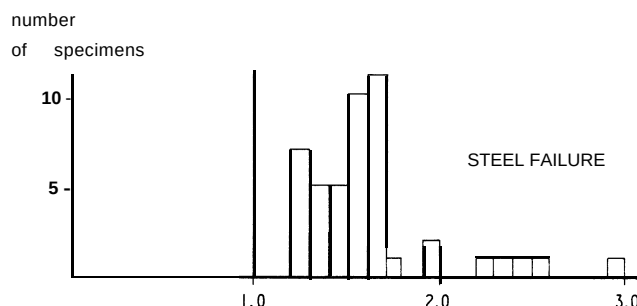


Fig. 3.7-Ratio of actual to predicted tensile capacity according to Eq. (3.1) for steel failure (after Klingner and Mendonca 1982)

3.2.3.2 Concrete cone failure -When the embedment of an anchor or group of anchors is insufficient to develop the tensile strength of the anchor steel, a pullout cone failure of the concrete [see Fig. 3.2(d)] is the principal failure mode. When the spacing of anchors or location of an edge [Fig. 3.2(e)] interferes with the development of the full cone strength of an anchor, its capacity will be reduced.

The angle of the failure cone, measured from the axis of the anchor, varies along the failure surface and shows considerable scatter. In ACI 349, Appendix B, ACI Committee 349, 1985) the angle of the failure cone of headed and expansion anchors is assumed as 45°. According to Cannon*, in the case of expansion anchors the angle varies from about 60° for short embedments ($l_d \leq 2$ in) to 45° for $l_d \geq 6$ in. According to Rehm, Eligehausen, and Mallee 1988, the angle varies between approximately 50° and 60°, (mean value 55°) and tends to decrease with increasing anchorage depth.

The following formulas have been developed to describe behavior of headed studs, expansion, and undercut anchors.

*Cannon, Robert W., correspondence to ACI Committee 355, Nov. 1986.

Cannon, Robert W., correspondence to ACI Committee 355, Sept. 1988.

This correspondence is filed at ACI headquarters and is available at cost of reproduction and handling at time of request.

ACI 349, Appendix B, limits the tensile capacity of the cone failure of an anchor, or **group** of anchors, to a uniform stress of $4 \phi \sqrt{f'_c}$ (psi) on the stress cone surface of the anchors.

$$F_u = 4 \phi (\sqrt{f'_c}) A, lb \quad (3.2)$$

- ϕ = strength reduction factor
 = 0.85 for uncracked concrete
 = 0.65 in zone of potential cracking
 A = the summation of the projected areas (in.²) of individual stress cones minus the areas of overlap and of any area, or areas, cut off by intersecting edges.

Note: Other reductions are made based on member thickness relative to embedment and the area of fabricated anchor heads (see Fig. 3.8).

ACI 349 has no requirements for minimum center-to-center spacing of single anchors or anchors belonging to a group.

Fig. 3.9 shows the frequency diagram of the ratio of actual to Predicted tensile capacity of headed anchors. Theoretical capacity was calculated according to Eq. (3.2). The tests were described by Klingner and Mendonca (1982a), and were evaluated by Cannon*. Tested were individual anchors with large and small edge distances and anchor groups. In all tests a concrete cone failure occurred.

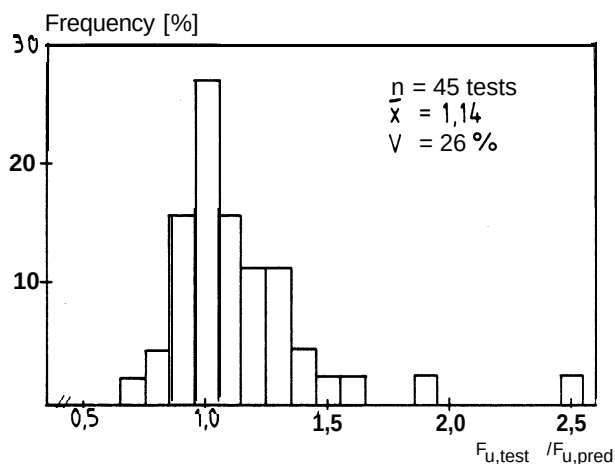


Fig. 3.9 -Ratio of actual to predicted tensile capacity of headed anchors according to Eq. (3.2) (from Cannon, 1984 **)

If an anchor is installed too close to an edge, the anchor will fail before developing the concrete cone strength. Therefore, for headed anchors, ACI 349 requires that the minimum edge distance m to the center of the anchor be sufficient to prevent a side cone failure. The following equation is suggested in the ACI 349 Commentary for determining this minimum value.

$$m = D \sqrt{\frac{F_u}{73 \sqrt{f'_c}}}, \text{ in.} \quad (3.3)$$

where

D = anchor diameter, in.

F_u = ultimate tensile strength of anchor, psi

f'_c = compressive strength of concrete, psi

If this requirement cannot be satisfied, stirrup or tie reinforcement should be provided.

Cannon+ found that for embedments less than 6 in., ACI 349 becomes increasingly conservative with decreasing embedment. He has proposed a modification to Eq. (3.3) to provide a better fit to test data. For embedments less than 6 in., this modification would increase the angle of the failure cone, measured from the axis of the anchor.

$$\text{For } l_d < 3 \text{ in.: } \alpha = 62 - 1.1 (l_d)^2, \text{ deg} \quad (3.4)$$

$$\text{For } l_d \geq 3 \text{ in. but } < 6 \text{ in.: } \alpha = 45 + 0.79 (6 - l_d)^2, \text{ deg} \quad (3.5)$$

With respect to the minimum edge distance he reported the results of tests which indicated a direct relationship between anchor load and side cone failure.** He suggested Eq. (3.6) instead of Eq. (3.3) as a more correct lower bound for the edge distance for headed anchors:

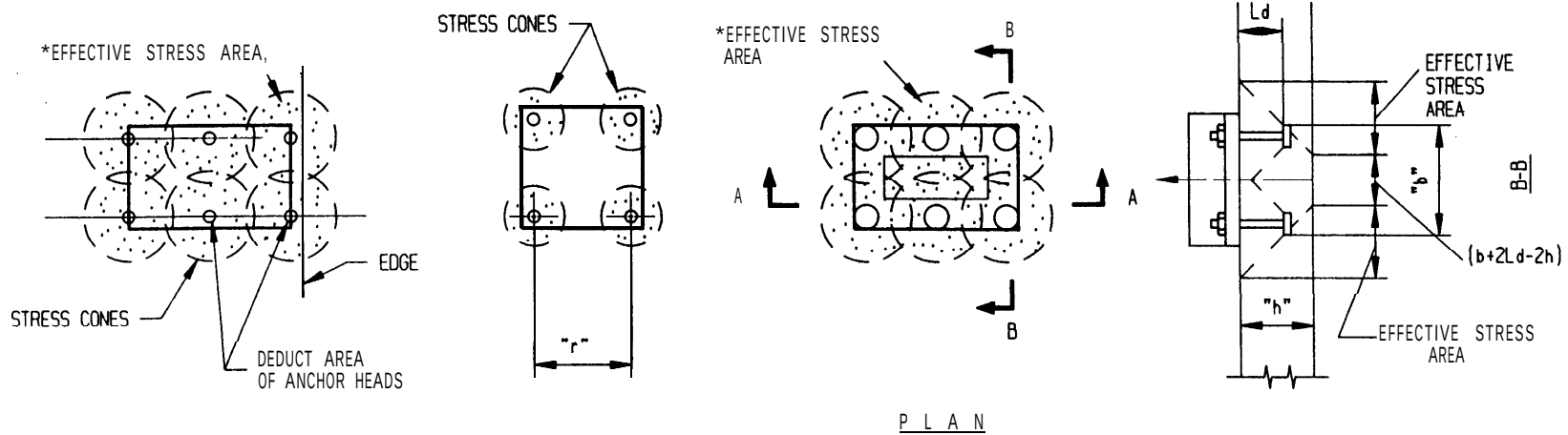
$$m = F_{ut} \sqrt{\frac{3500}{f'_c}} \frac{1}{10}, \text{ in.} \quad (3.6)$$

F_{ut} = ASTM-specified tensile strength of the anchor bolt, kips

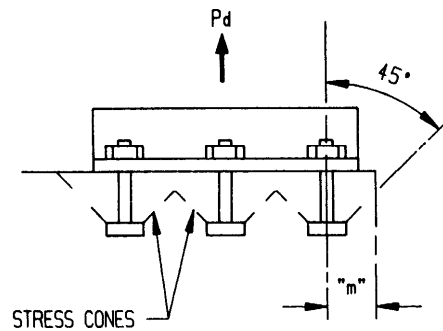
*Cannon, private correspondence, 1988, previously cited (see footnote p 14).

+Cannon, private correspondence, 1986, previously cited (see footnote p 14).

**Cannon, Robert W., Letter to ACI 355, "Comparison of Testing Edge Conditions and Anchor Spacing with Predictions", Dec. 1984.

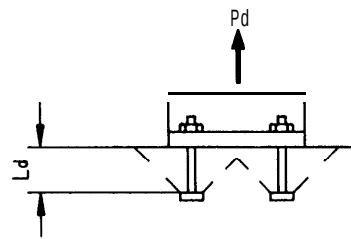


*REDUCE BY THE TOTAL BEARING AREA OF THE ANCHOR STEEL.



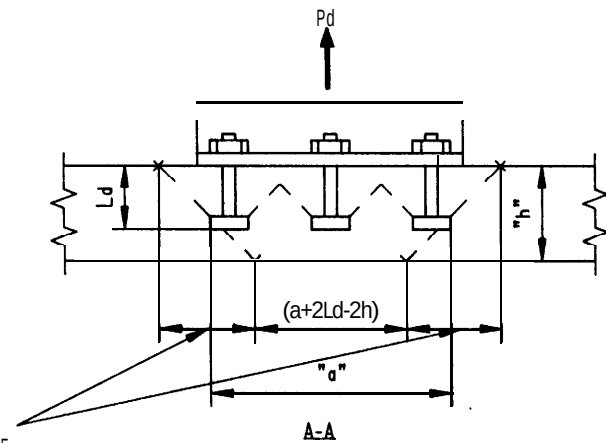
GROUP EFFECT CONTROLS

A) Effective stress area for anchorage pullout



INDIVIDUAL STRESS CONE CONTROLS

EFFECTIVE STRESS AREA



STRESS AREA REDUCTION FOR LIMITED DEPTH (Ar)
 $A_r = (a+2Ld-2h)(b+2Ld-2h)$

*REDUCE BY THE TOTAL BEARING AREA OF THE ANCHOR STEEL

B) Stress area reduction for limited depth A

Fig. 3.8-ACI 349 method for determining effective stress areas

The average failure load for a side cone (bursting) failure is given as:

$$F_u = 15m \sqrt{\frac{f'_c}{3500}}, \text{ kips} \quad (3.7)$$

where

m = actual edge distance, in.

For expansion and undercut anchors, Eligehausen, Fuchs, and Mayer (1987 and 1988), derived Eq. (3.8a) from 287 test series with single anchors with large edge distances showing concrete cone failure.

$$F_u = 15l_d^{1.5} \sqrt{f'_c}, N \quad (3.8a)$$

where

F_u = average ultimate load, N
 l_d = embedment depth (see Fig. 3.10), mm
 f'_c = average compressive strength of concrete cylinders (6 by 12 in.) at time of testing, N/mm²

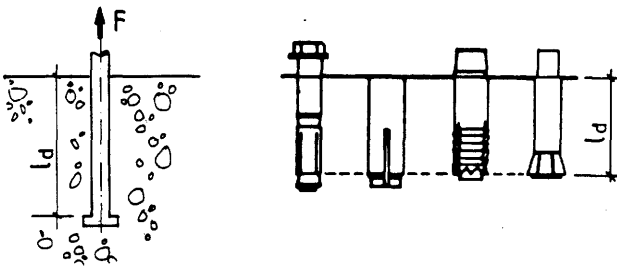


Fig. 3.10 -Illustration of embedment depth as used in Eq. (3.8a) and (3.8b)

Results of an additional 196 tests on headed studs showed a similar relationship (from Rehm, Eligehausen, and Mallee 1988).

$$F_u = 17l_d^{1.5} \sqrt{f'_c}, N \quad (3.8b)$$

In the original equation the concrete strength was measured on cubes with a side length of 200 mm (8 in.). Eq. (3.8a) and (3.8b) assume f'_c (cylinder) = 0.82 f'_{cc} (cube).

The tests with expansion, undercut and headed studs included anchorage depths from 40 to 525

mm (1 9/16 to 20 1/2 in.) and concrete strengths $f'_c = 20$ to 50 N/mm² (2900 psi to 7150 psi). Fig. 3.11 shows a histogram of the ratio of measured to predicted failure load.

The average failure loads given in Eq. (3.8) can only be obtained if the distances between anchors are large enough so that concrete cones do not overlap each other. Assuming an angle of the failure cone $\alpha \approx 55^\circ$ the critical distance is approximately three times the embedment depth. The failure load of a two-point fastening results in:

$$F_{u2} = \chi_a \times F_{u1} \quad (3.9)$$

where

F_{u1} = ultimate failure load, single anchor, from Eq. (3.8)

$$\chi_a = 1 + a/a_{crit} \leq 2 \quad (3.10)$$

where

a = distance between center of anchors
 a_{crit} = critical distance between center of anchors
 $= 3l_d$, where l_d is the depth of embedment.

Eq. (3.9) leads to the x-method for calculating the ultimate capacity of multiple anchor fastenings. For the calculation of the ultimate load of quadruple fastenings the χ_a factors can be derived separately for both directions and combined in product form as follows.

$$F_{u4} = \chi_{a1} \times \chi_{a2} \times F_{u1} \quad (3.11)$$

$$\chi_{ai} = 1 + a_i/a_{crit} \leq 2 \quad (3.12)$$

where

a_i = spacing in direction i

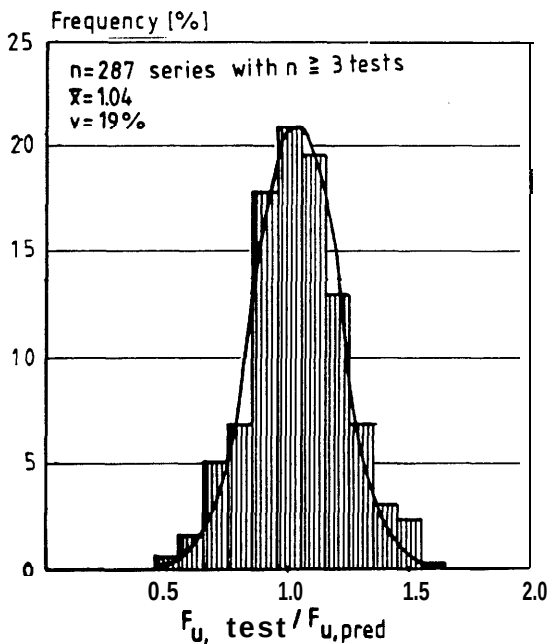


Fig. 3.11 (a) -Ratio of actual to predicted tensile capacity for concrete cone failure of individual expansion and undercut anchors away from edges according to Eq. (3.8a). (from Rehm, Eligehausen, and Mallee 1988, and Eligehausen, Fuchs, and Mayer 1987 and 1988)

Fig. 3.12 shows the capacity of quadruple fastenings for headed studs, expansion and undercut anchors as a function of the ratio of anchor spacing to embedment depth as measured in tests and calculated according to Eq. (3.11).

Eq. (3.9) and (3.11) can also be extended for multiple anchorages with any number of a_i as the distance a_{tot} between the outer anchors, and the χ_a -value is limited to $\chi_a \leq n$ with n = number of anchors in one direction. This is provided that the spacings between the individual anchors are smaller than $a_{crit} = 31$, and the anchor plate is sufficiently stiff to assure an even distribution of tension forces to all anchors (see Rehm, Eligehausen, and Mallee 1988). The X-method can also be extended to take account of load eccentricities (Riemann 1985).

Fig. 3.13 shows the ratio of actual to predicted tensile capacity of groups of headed studs. In the tests the number of anchors was varied between 4

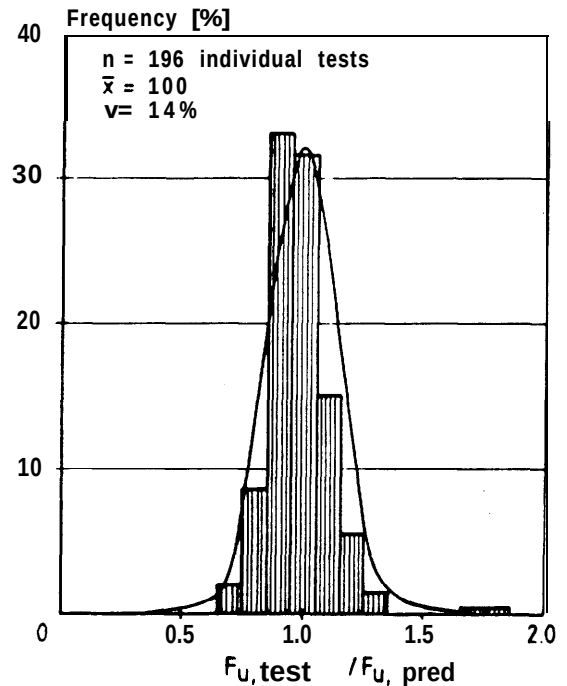


Fig. 3.11(b) -Ratio of actual to predicted tensile capacity for concrete cone failure of individual headed anchors away from edges according to Eq. (3.86). (from Rehm, Eligehausen, and Mallee 1988)

and 36, the spacing of the outer anchors between 100 and 875 mm and the spacing of the individual anchors between 0.541, and $2.2l_d$. The groups were loaded by a concentric tension load which was equally distributed to all anchors.

Eq. (3.13) covers the influence of edge distances, a , smaller than critical:

$$F_{u,m} = \chi_{am} \cdot F_u \quad (3.13)$$

where

$$\chi_{am} = 0.3 + 0.7 \frac{a_m}{a_{m,crit}} \leq 1 \quad (3.14)$$

$a_{m,crit}$ = critical distance from free edge
= $1.5 l_d$

l_d = actual embedment length
 F_u = ultimate failure load, single anchor
to be taken from Eq. (3.8)

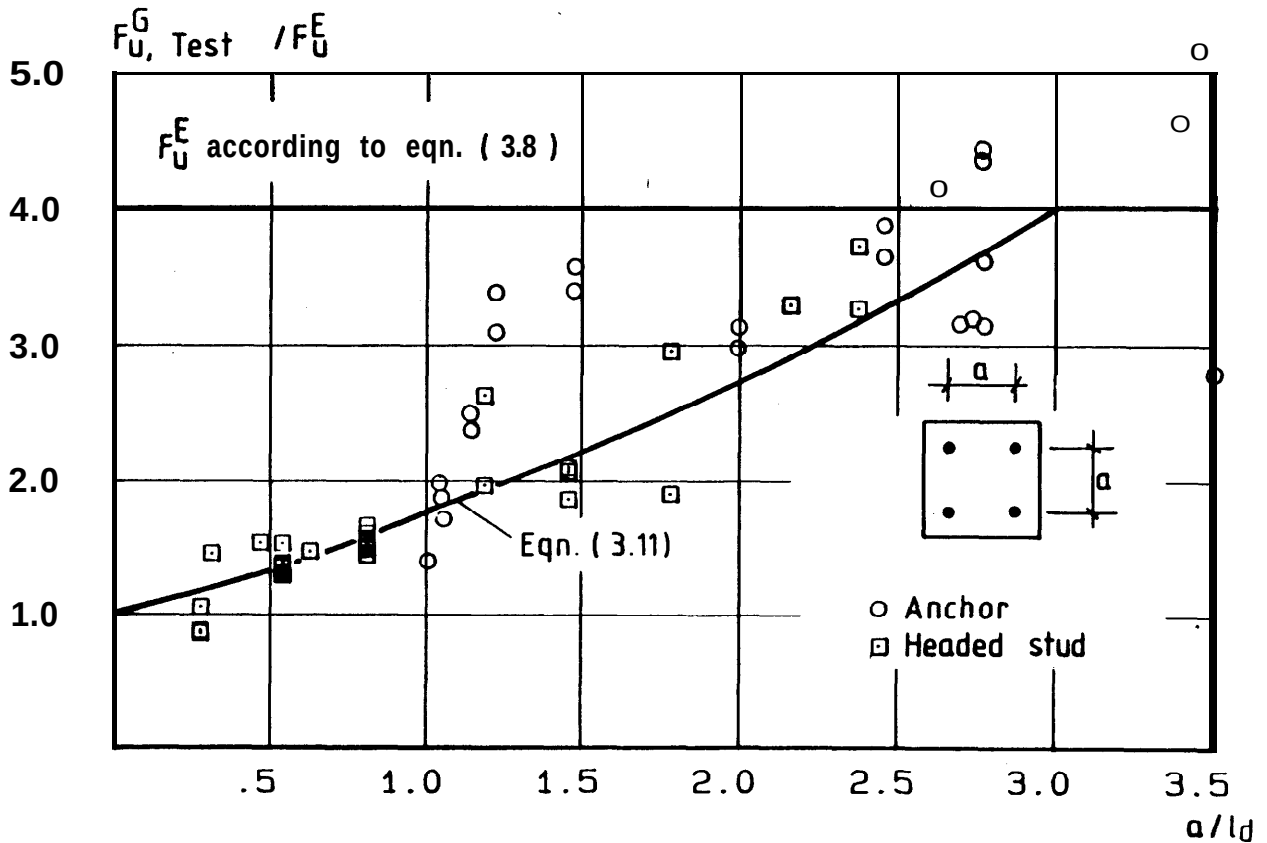


Fig. 3.12-Ratio of actual failure load of a group of anchors to the predicted value for an individual anchor as a function of the ratio of anchor spacing to embedment depth (from Rehm, Eligehausen, and Mallee 1988)

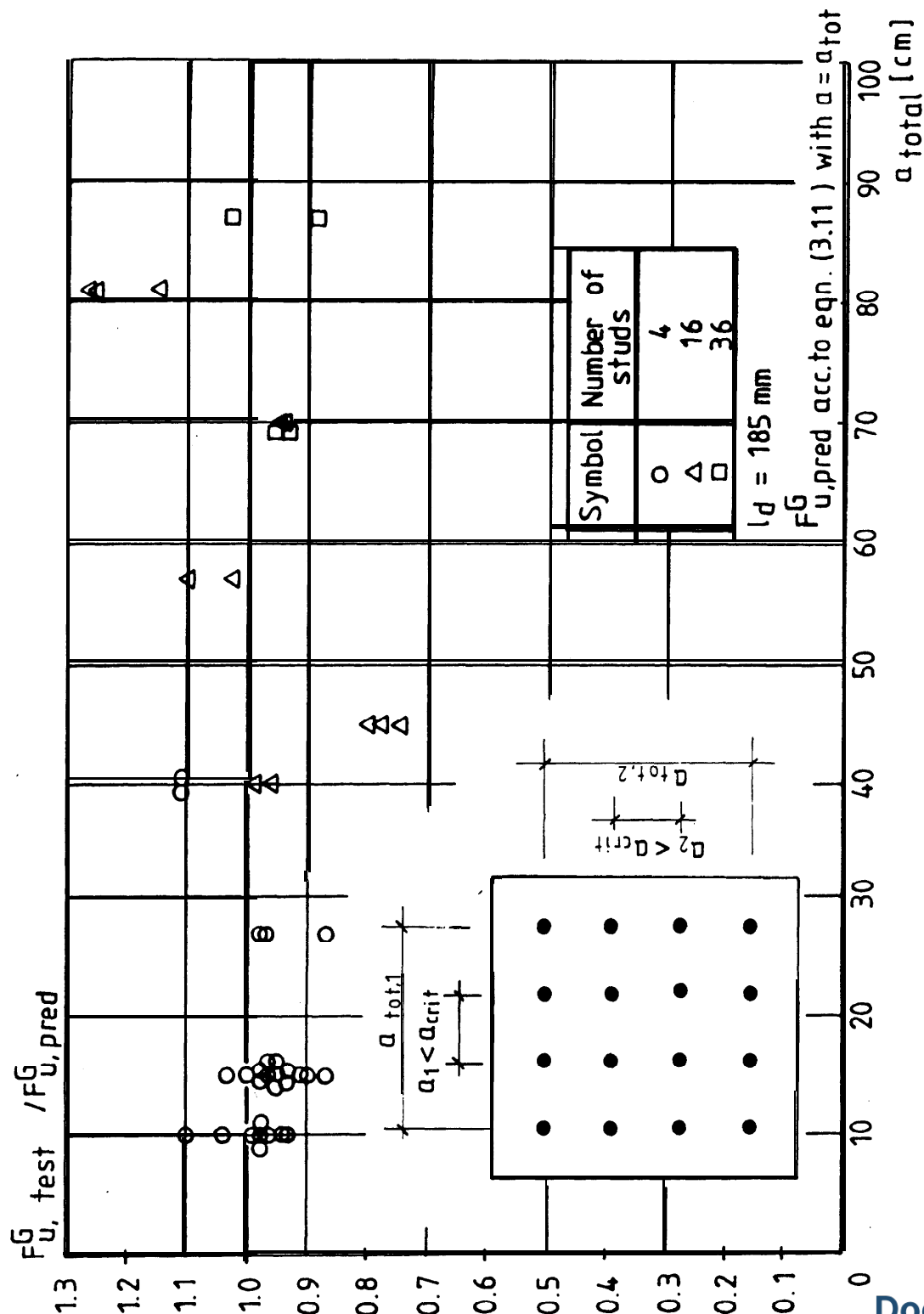


Fig. 3.13 — Ratio of actual to predicted tensile capacity of groups with headed anchors as a function of the spacing of the outer anchors (from Rehm, Elgehausen, and Mallee 1988)

Fig. 3.14 shows a comparison of test results with the theoretical values according to Eq. (3.13). It should be noted, however, that minimum distances from the free edge are necessary for headed studs in order to allow proper concreting and avoid local spalling of concrete. Minimum edge distances for expansion and undercut anchors are necessary to avoid splitting of concrete during installation and expansion of the anchors.

If anchors are located in a corner [see Fig. 3.15(b₃)], the factors χ_{am} are calculated separately for each direction and then the two x-factors are multiplied.

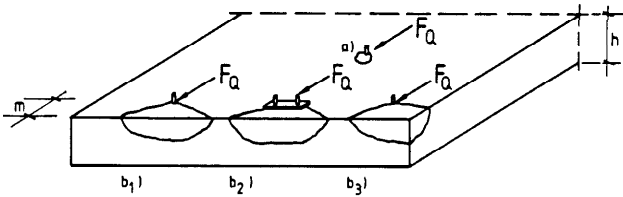


Fig. 3.15 – Typical failure modes of anchors loaded in shear (from Rehm, Eligehausen, and Mallee 1988)

Bode and Roik (1987), evaluated data of 106 tests with headed studs to arrive at Eq. (3.15).

$$F_u = 12 l_d^{3/2} (1 + d_h/l_d) \sqrt{f'_c}, N \quad (3.15)$$

where

- F_u = average failure load, N
- l_d = embedment length, mm
- d_h = head diameter, mm
- f'_c = concrete cylinder strength at time of testing, N/mm²

Fig. 3.16 compares the measured failure loads of headed studs with the values according to Eq. (3.15).

Bode and Roik (1987), assume the critical center-to-center spacing of neighboring headed anchors as:

$$a_{crit} = 4 l_d \quad (3.16)$$

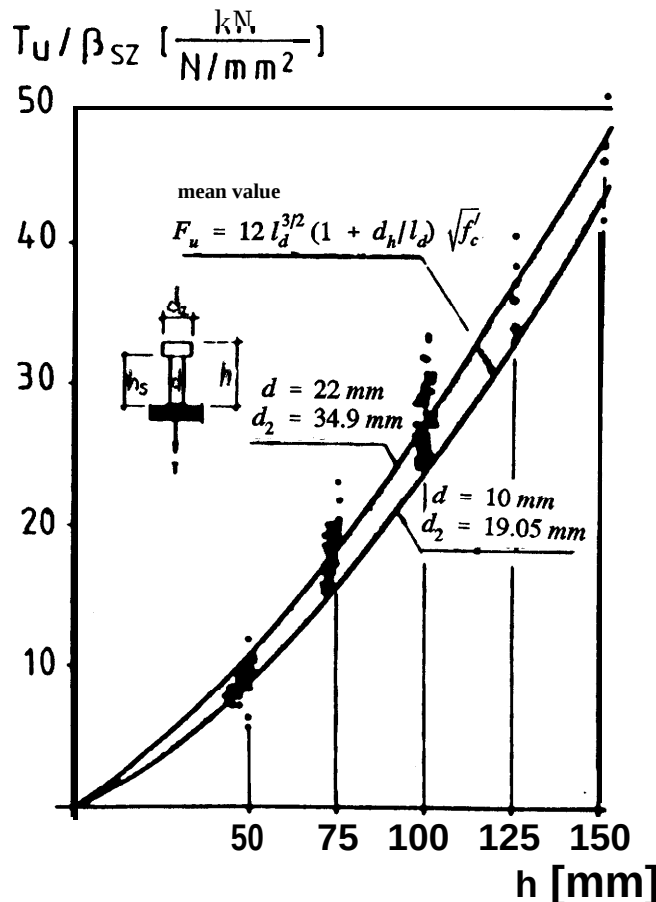


Fig. 3.16 - Measured failure loads compared to Eq. 3.15 (where β_{sz} = concrete splitting strength) (from Bode and Roik 1987)

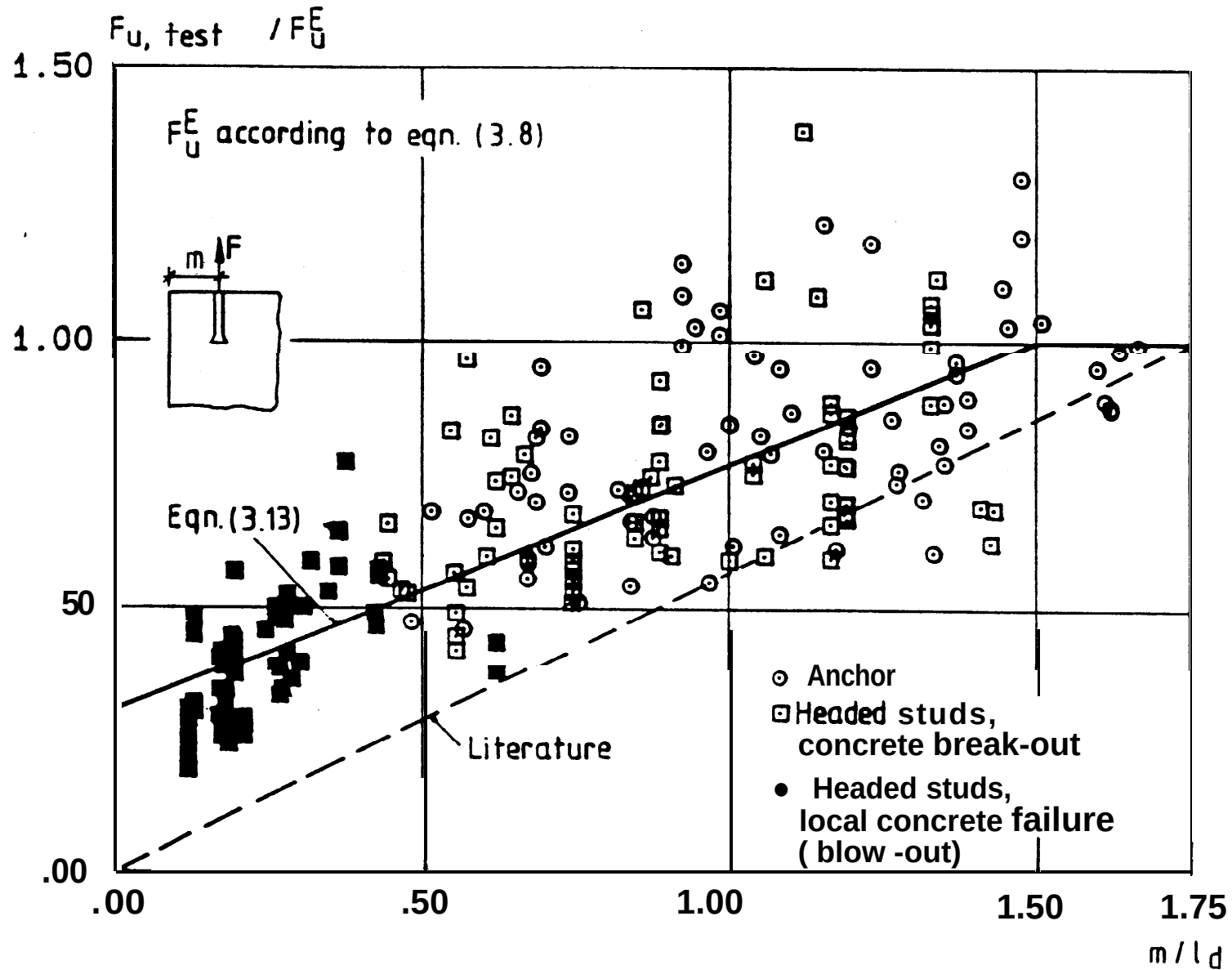


Fig. 3.14-Ratio of actual failure load of an individual anchor close to the edge to the predicted value for an anchor with large edge distance (from Lehman, Eligehausen, and Mallee 1988)